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Carbon capture and storage potential in coal-fired plant in Malaysia—A review

Tick Hui Oh *

Faculty of Engineering and Technology, Malaysia Multimedia University (MMU), 75450 Bukit Beruang, Malacca, Malaysia

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ABSTRACT

Secure, reliable and affordable energy supplies are necessary for sustainable economic growth, but increases in associated carbon dioxide (CO_2) emissions, and the associated risk of climate change are a cause of major concern. Experts have projected that the CO_2 emissions related to the energy sector will increase 130% by 2050 in the absence of new policies or supply constraints as a result of increased fossil fuel usage. To address this issue will require an energy technology revolution involving greater energy efficiency, increased renewable energies and nuclear power, and the near-decarbonisation of fossil fuel-based power generation. Nonetheless, fossil fuel usage is expected to continue to dominate global energy supply. The only technology available to mitigate greenhouse gas (GHG) emissions from large-scale fossil fuel usage is carbon capture and storage (CCS), an essential part of the portfolio of technologies that is needed to achieve deep global emission reductions. However, CCS technology faces numerous issues and challenges before it can be successfully deployed. With Malaysia has recently pledged a 40% carbon reduction by 2020 in the Copenhagen 2009 Climate Summit, CCS technology is seen as a viable option in order to achieve its target. Thus, this paper studies the potential and feasibility of coal-fired power plant with CCS technology in Malaysia which includes the choices of coal plants and types of capture technologies possible for implementation.

Contents

1. Introduction

Carbon sequestration can be defined as the capture and secure storage of carbon that would otherwise be emitted to, or remain, in the atmosphere. The removal of CO_2 directly from industrial or utility plants and subsequently storing it in secure reservoirs is called carbon capture and storage (CCS). The rationale behind CCS is to enable the continuous usage of fossil fuels while reducing the emission of CO_2 into the atmosphere, and thereby mitigating global climate change. A complete end-to-end CCS system is a dedicated assemblage of various technologies and components, many of which are already used in other settings and working together to prevent CO_2 from entering the atmosphere. CCS is an integrated process, made up of three distinct parts; carbon capture, transport and storage or sequestration. Capture technology aims to produce a concentrated stream of CO_2 that can be compressed,

* Tel.: +60 6 2523258; fax: +60 6 2316552.
E-mail address: thoh@mmu.edu.my.

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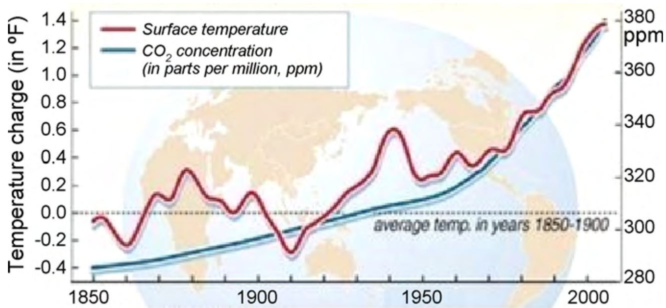


Fig. 1. The correlation between CO_2 concentrations in the atmosphere and the earth's surface temperature.

transported and stored. Transport of captured CO_2 to storage locations is most likely to be via pipeline. Storage or sequestration of the captured carbon is the final part of the process.

Most scientists agree that CO_2 emission need to be reduced universally by 30–60% by the year 2050 to keep CO_2 concentration in the atmosphere below 550 ppm (parts per million) so that to limit the temperature rise between 2.4 and 2.8 °C compared to pre-industrialized levels. Over the past several centuries, the atmospheric CO_2 concentrations have increased steadily and have now risen close to 400 ppm from the pre-industrial level of below 300 ppm [1] as shown in Fig. 1. Kyoto Protocol states that the European Union (EU) should reduce greenhouse gas (GHG) emissions by an average of 5% of its 1990 level over its five-year period commitment (2008–2012) [2]. End-of-pipe technologies which have now been collectively known as carbon capture and storage (CCS) is gaining momentum in recent years to provide a viable alternative to achieve this ambitious target [3]. It has become common knowledge that hydrocarbon is the main culprit in CO_2 emission. There are potential in power generation and energy supply sector in which the CCS can be applied as these are large point sources of CO_2. A coal powered plant is estimated to emit between 6–8 Mt CO_2 per year while an oil fired single cycle power plant and a natural gas combined cycle power plant emit one third and two third of the coal-fired plant, respectively. The earth has a natural storage reservoir which can contain abundance of CO_2 and currently, the amount of this storage being used is approximately less than 0.1 Gt CO_2 per year which is about 1.42% only [4].

The long-term solution of reducing GHG emissions is to uncouple energy use and CO_2 release. It can also be done by transition to renewable sources such as biomass, hydro, nuclear, solar, wind, geothermal and tidal energy. However, these energy sources and technologies cannot fully substitute fossil fuels for the time being, particularly given the numerous ways in which such fuels are used and the current economic framework energy [5]. It has been estimated that lifetime emissions from power plants projected to be build for the next 25 years are equivalent to all the emissions for the last 250 years [6]. However, an alternative possibility is for fossil fuels to continue to form the basis of our energy infrastructure and CO_2 to be captured from the atmosphere and stored for a long period. The atmosphere is there as a convenient repository for wastes and both the geological and oceans formations can be used to store CO_2. Still, CCS technology faces many challenges to be successful, full-scale demonstration and commercial deployment including issues such as: financing large-scale demonstration projects and integration of CCS into GHG policies; higher cost and efficiency penalty of CCS technologies; development and financing of adequate CO_2 transport infrastructure; development of legal and regulatory frameworks to ensure safe, permanent CO_2 storage; adequate public consultation; and developing capacity and awareness in rapidly growing fossil-based economies.

This paper begins with the brief history on how the energy policy has evolved over the years in Malaysia and leads to the country's involvement in the clean development mechanism (CDM) from the Kyoto Protocol. Then the energy scenario in the country and its current CO_2 emissions update are presented. This is followed by discussions on coal-fired power plant and the estimated cost of CCS application. As Malaysia is seen to have great potential in applying CCS technology in its coal-fired power plants, some choices of such plants are reviewed and recommended here together with the several types of possible capture technologies.

2. Malaysia energy policy

The energy policy in Malaysia has evolved over the past few decades, instigated mainly by the 1970s world oil crisis. The National Petroleum Policy formulated in 1975, aimed at regulating the oil and gas industries in order to achieve overall economic development needs in Malaysia. The National Energy Policy (1979) had identified the following major objectives; (i) to ensure adequacy, security and cost-effectiveness of energy supply, (ii) to promote efficient utilization of energy, (iii) to discourage wasteful patterns of energy consumption, and (iv) to minimize any negative environmental impacts in the energy supply chain. With regard to the energy supply objectives, policy initiatives have aimed at extending the life of domestic depletable energy resources and at the same time diversifying from oil dependency to other energy sources [7].

Hence, the announcement of the National Depletion Policy in 1980 and a year later, the Four-Fuel Diversification Strategy 1981 was implemented, with the former to prolong lifespan of the country's oil reserves for future security and stability of oil supply and the latter to pursue balanced utilization of oil, gas, hydro and coal. This policy was replaced in 1999 with the Five-Fuel Diversification Strategy and renewable energy (RE) was made the fifth fuel in the energy supply mix, along with natural gas, coal, hydro and oil. The fuel diversification strategy saw the drastic drop of oil in the energy mix contribution, from a high 87.9% in 1980 down to a mere 2.2% in 2005, with the remaining 70.2% and 21.8% contributed by natural gas and coal respectively [8]. Under the five-fuel policy also, the direct result to reduce the dependency on oil and gas has seen new development of coal-fired plants. In peninsular Malaysia, besides the state-owned Kapar mixed-fuel 1600 MW (1988) and the 2100 MW Janamanjung (2003) facilities, two other coal plants; Tanjung Bin in Johor (2100 MW) and Jimah in Negeri Sembilan (1400 MW) are owned by independent power producers. Sarawak derives 220 MW from its Sejingkat coal plant while the Silam plant will be the first coal-fired power plant (300 MW) in Sabah [9].

Currently, most of the coal supply is imported and as the source gaining importance in the country's energy scene, there are continuing efforts to enhance the security of supply by exploring the potential for development of local sources, particularly in Sarawak, as well as securing long-term supplies from abroad. However, for every megawatt-hour (MWh) of electricity generated, conventional coal-fired power plants emit nearly twice the CO_2 of that a modern natural gas combined cycle power plant [10]. Furthermore, coal will be totally exhausted one day and cause energy security threat, plus their significant and prolong contribution to the emission of GHGs from their combustions definitely hastens the global warming as well. Thus, following the five-fuel policy, the government has ratified the Kyoto Protocol in September 2002 and as a non-Annex 1 country, Malaysia can utilize CDM to reduce domestic CO_2 emissions as well as transfer advanced technologies from developed countries.

3. Clean development mechanism (CDM)

The damage inflicted by global warming is happening far faster than anticipated. Since the Kyoto Protocol was inked in 1997 among 158 countries to fight global warming through GHGs emission reduction, CO_2 in particular, the world climate pattern has worsened at an accelerated rate beyond expectation. Since the United Nations Framework Convention on Climate Change (UNFCCC) was signed at the Earth Summit in 1992, other Annex I countries have already committed in projects that aim at minimizing CO_2 emission by 5% of their 1990 levels over the commitment period from 2008–2012, with heavier burden placed on Annex I countries under the principle of common but differentiated responsibilities in article 10 of the Kyoto Protocol. This is based on two main principles; firstly, those countries are economically and technologically capable and secondly, they have been responsible for the introduction and continuous generation of enormous amount of GHG per person [11] and reaped the most benefits.

The clean development mechanism (CDM) is the only mechanism in the Kyoto Protocol that offers a new avenue for emission reduction in a cost-effective way between the industrialized (Annex I) and developing (non-Annex I) countries, which do not have any obligatory emission reduction target. The innovation of CDM is that it allows the market to determine where it is cheapest to reduce emissions, which should significantly lower the cost of compliance globally. As a non-Annex I country, the CDM is thus the only mechanism under the protocol that is relevant for Malaysia. CDM facilitates co-operative projects between developed and developing countries with the opportunity for additional financial and technological investments in GHG reduction projects. The GHG reductions achieved by each CDM project will be quantified in standard units known as Certified Emission Reductions (CERs), a form of carbon credits. It involves the trading of emission reductions that are resulting from a specific project (called CERs once such reductions are certified) to countries that can use these CERs to meet their targets. In return for the CERs, there will be a transfer of money to the project that actually reduces the GHGs [12].

An analysis of 1077 CDM projects registered by non-Annex I countries and 1085 by Annex I countries on May 30th 2008 by UNFCCC found that almost 54.28% of them are energy industries projects which involve the generation of zero emission energy (electricity or heat) from renewable sources and fossil fuels. The energy industry can also mitigate emissions through fossil fuel switching or supply-side energy efficiency projects which involve improvements to increase the efficiency of a power or heat generation plant; for example, changing from open cycle to combined cycle gas turbines. In projects distribution, Malaysia has 28 projects (2.6%) as indicated in Fig. 2 and has managed to secure 2,422,435 (1.12%) CERs [13].

GHGs emission reduction in industrial activities, energy efficiency and energy conservation system, change to cleaner fuels and development of renewable and alternative energy sources are among potential candidates for CDM projects, as summarized in Table 1. An example of the CDM project related to coal-fired plant that offer numerous benefits are given below [14]:

i. Environmental benefits – with capture technology extended to coal-fired power plant like the schematic diagram shown in Fig. 3, the desirable environmental impacts can be obtained:
   - CO_2 as a potent GHG that contributes to global climate change is captured through absorption/adsorption process.
   - Sulphur (like hydrogen sulphide, H_2S), which emits strong pungent adours is removed through absorption or adsorption technology.
   - Volatile organic compounds (VOCs) and non-methane organic compounds (NMOCs), which contributes to ground-level ozone (O_3) formation (smog) and hazardous air pollutants (HAP) are removed (or emission reduced) through thermal treatment, including proper flaring and combustion.

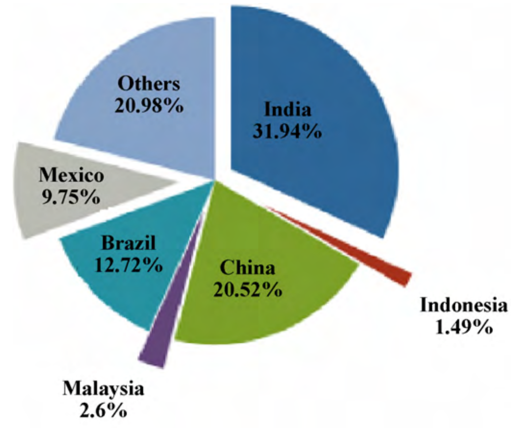


Fig. 2. Registered projects by non-Annex I countries [13].

Table 1
Potential CDM projects in different sector [17,18].

Sectors	Potential projects/activities
Agriculture	▪ Improvement in cultivation practices to reduce methane emissions. ▪ Reduction of energy use through demand side management. ▪ Improvement in use of agrochemical.
Building (residential, commercial and government)	▪ Energy efficient design of buildings. ▪ Energy efficient appliances. ▪ Energy conservation measures. ▪ Fuel switching in households and commercial boilers. ▪ Use of renewable energy sources.
Energy (nuclear energy, excluded from CDM)	▪ Development of renewable energy sources (hydro, solar, wind, biomass, etc.). ▪ Clean coal technologies. ▪ Fuel substitution measures. ▪ Improvement in power transmission and distribution network. ▪ Reduction of leakage in transport, handling and distribution of oil and gas.
Forests	▪ Afforestation and reforestation.
Industry and manufacturing	▪ Energy conversion and energy efficiency measures. ▪ Process modification in order to lower emissions. ▪ Change of feedstock in boilers.
Mining	▪ Coal bed methane recovery and reduction of methane emissions. ▪ Control of fires in mines. ▪ Energy efficient systems.
Transport	▪ Introduction to alternate fuel. ▪ Switch over to cleaner fuel. ▪ Fuel efficiency measures. ▪ Improvement of public transport. ▪ Urban planning and traffic management.
Waste	▪ Landfill gas recovery and use. ▪ Waste to energy conversion activities. ▪ Composting from municipal organic waste.

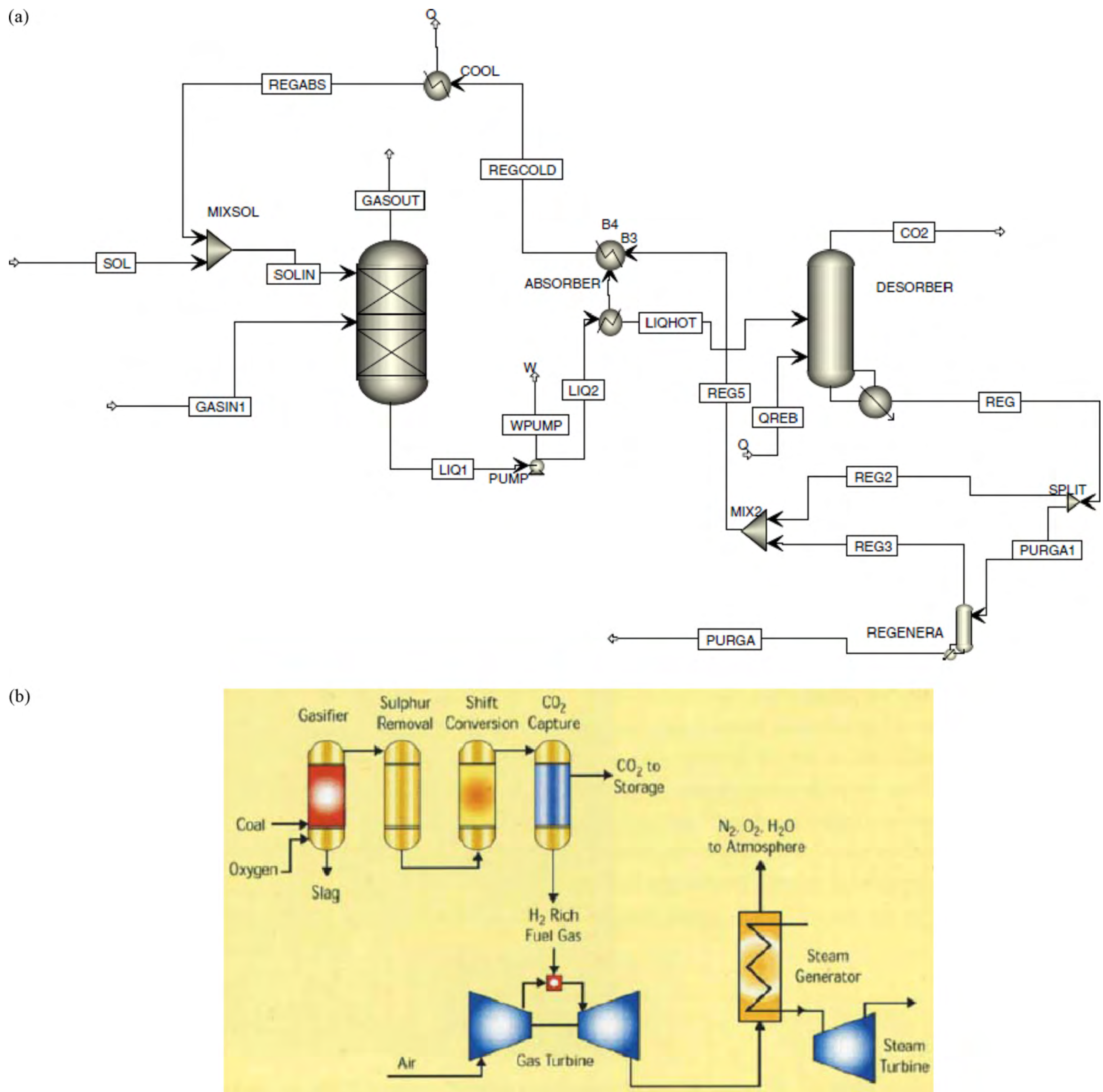


Fig. 3. A coal-fired plant project process flowchart: (a) MEA absorption process flowsheet [15]; (b) an adsorption process flowsheet [16].

- The produced slug is converted to commercials products through material technology.

ii. Social benefits – the social benefits from the coal-fired power plant with capture technology can be summarized as follows:
- Reduction of GHGs and HAP that can cause variety of health problems such as cancer, respiratory irritation and central nervous system damage.
- Abatement of the pungent odours. This will result in a positive consequence on the quality of life for the society and a significant economic impact by contributing to higher local property values involved.
- Such project will directly and indirectly generate employment opportunities for the local communities.

iii. Economic benefits – this project creates jobs associated to design, construction and operation of energy recovery systems. Besides involving engineers from various fields, construction firms, equipment vendors and utilities or end-users of the power produced, much of the cost is spent locally for drilling, piping, construction and operational personnel, helping communities to realize economic benefits from increased employment and sales.

iv. Stakeholder consultation – under the Kyoto Protocol, it is compulsory for the developer to organize a series of stakeholder consultation, so as to ensure that public concerns about the project are taken into consideration. Within the context of the discussion on the proposed projects, explanations about the environmental, economic and social impacts of construction and operation will be shared or made available to public. The inputs from local stakeholders will then be obtained through surveys and compiled into three categories; (a) governmental organizations, (b) public and private entities and non-government organization, and (c) communities.

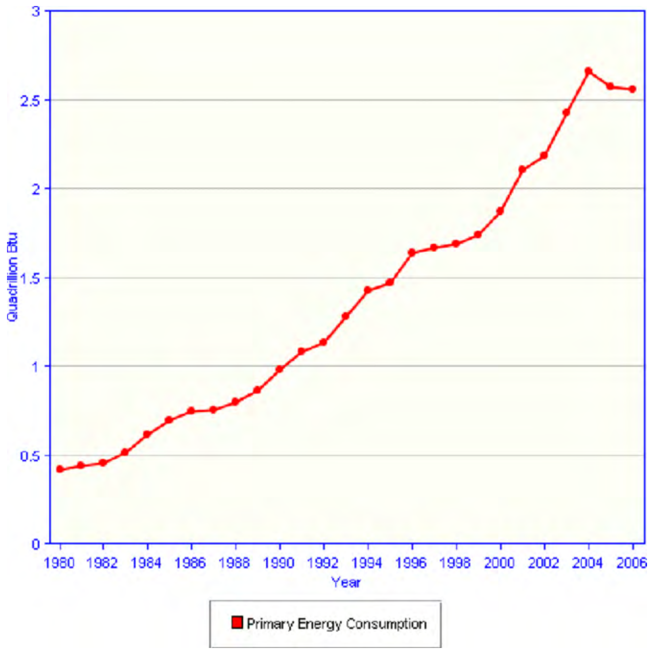


Fig. 4. Total primary energy consumption in Malaysia [19].

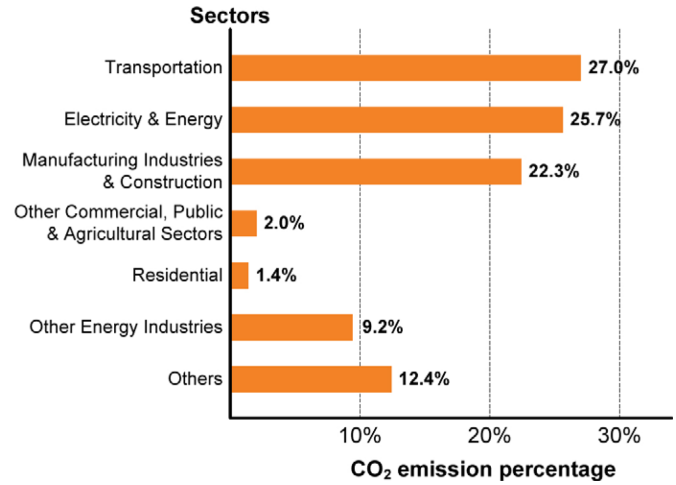


Fig. 5. CO_2 emissions by sectors in Malaysia [21].

v. Technology transfer – with bilateral or multilateral CDM projects, all parties under the Kyoto Protocol are called upon to cooperate for the effective transfer of technology between foreign and local entities. The local partner would then be able to diffuse a more efficient and less carbon-intensive technology in order to duplicate the intended project when it is economically and technically feasible to do so.

4. Energy demand and CO_2 emissions

The total energy consumption in Malaysia was estimated at about 2.5 quadrillion Btu as in 2007, which is a 400% increase from the early 1980s as shown in Fig. 4, and is considered relatively high among developing countries and higher than some developed countries [19].

The final commercial energy demand in 2007 increased by 9.8% to settle at 44,268 ktoe compared to 40,318 ktoe in 2006. The share in commercial energy demand was highest for the industrial sector (43.2%) and transport sector (35.5%). This was followed by the residential and commercial (14.0%), non-energy (6.7%) and agriculture sectors (0.6%). All sectors showed an upward trend compared to the previous year. Malaysia's total installed electricity generation capacity as of end 2007 was 21,815 MW, an increase of 7.9% from 20,224 MW in 2006. Meanwhile, the total available capacity as of end 2007 was 20,789 MW. Electricity gross generation registered 101,325 GWh, an increase of 8.7% from 2006. On the other hand, the electricity consumption was 89,298 GWh, up 5.6% from 2006. In 2007, the electricity consumption from the residential sector increased 5.5% to register 1598 ktoe (18,572 GWh) from 2006, while the commercial sector also increased 9.6% to reach 2496 ktoe (29,009 GWh). The electricity consumption in the industrial sector recorded an increase of 3.2% to register at 3587 ktoe (41,689 GWh). The increase was influenced by higher gross domestic product (GDP) in the manufacturing sector recorded in 2007. The electricity consumption from the transport sector, however, dropped from

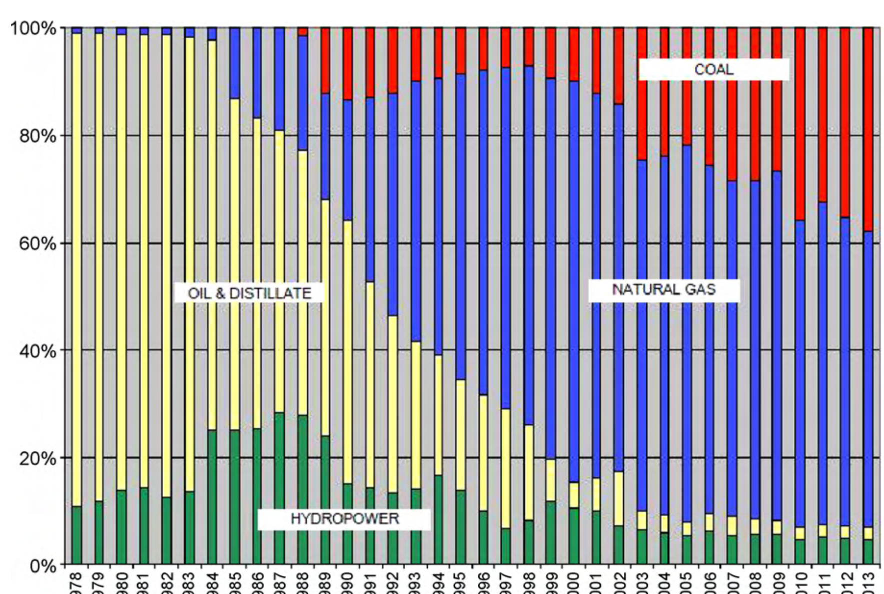


Fig. 6. Fuel mix trend in power generation in Malaysia [8].

Table 2
Coal consumption for electricity generation in Malaysia [14,23].

Year	Consumption ('000 tonnes)
2000	3634
2003	8408
2005	14,030
2006	14,492
2007	18,209
2008	19,095
2009	[a]21,000
2012	[a]28,000
2020	[a]36,000

[a] Projected.

5421 toe (63 GWh) in 2006 to 3554 toe (41 GWh) in the same period. Natural gas continues to provide the largest portion in this electricity generation mix with 56.6%, follows by coal and hydropower at 34.2% and 6.9%, respectively. The remaining 2.3% is contribution from oil and others [20].

It is evident that Malaysia is still very much dependent on fossil fuels in all its commercial energy demand and electricity generation. With the ever increasing energy demand in sustaining the country's growth in years to come, it is inevitable that CO_2 emission will worsen as long as fossil fuels are the main contributor in the energy mix. Fig. 5 depicts the CO_2 emission in Malaysia by sectors in 2005. Transportation sector in Malaysia which fully utilizes petroleum products is no doubt the main contributor in CO_2 emission, followed closely by the power sector which mainly consumes fossil fuels like natural gas and coal. Evidently, the plentiful yet inexpensive coal is catching up fast in the local energy scene as indicated in Fig. 6. As for the total energy consumption in Malaysia, coal formed 30% or 14,200 MW in 2008 and is expected to increase to 42% or 17,600 MW by 2013 [22]. Table 2 shows the amount of coal usage in electricity generation in Malaysia since year 2000 and the projected consumption up to 2020. Consumption of coal in electricity generation was 21.15 million tonnes from the seven plants (see Table 5) in 2008, with 8120 MW installed capacity and the total consumption is projected to increase to 36 million tonnes by 2020 [14].

With such consumption pattern, the total CO_2 emission in Malaysia has increased quite drastically towards the end of 1990s and exceeded 160 million metric tonnes by 2003, and has stayed above that level since, as illustrated in Fig. 7. The changes in energy sources for electricity generation have contributed to the emissions pattern in Malaysia. As a direct consequence of this policy, total CO_2 emissions from coal-fired power plants are projected to grow at a rate of 4.1% per year, reaching 98 million metric tonnes by year 2020, which is a 2.65-fold increase from 2005 [14]. It is a reality that CO_2 emissions will continue to increase as more constructions of new coal-fired power plants are underway to assure continuous growth of the country. With future energy demand expected to grow at a rate of 5–7.9% annually for the next 20 years from 2004 onwards [24], and with no dependable RE in sight, coal remains a very attractive option. Thus, if the CO_2 emissions from coal plants can be captured and properly managed through CCS system, the coal resources can definitely assure a secure and stable supply of energy for many years to come.

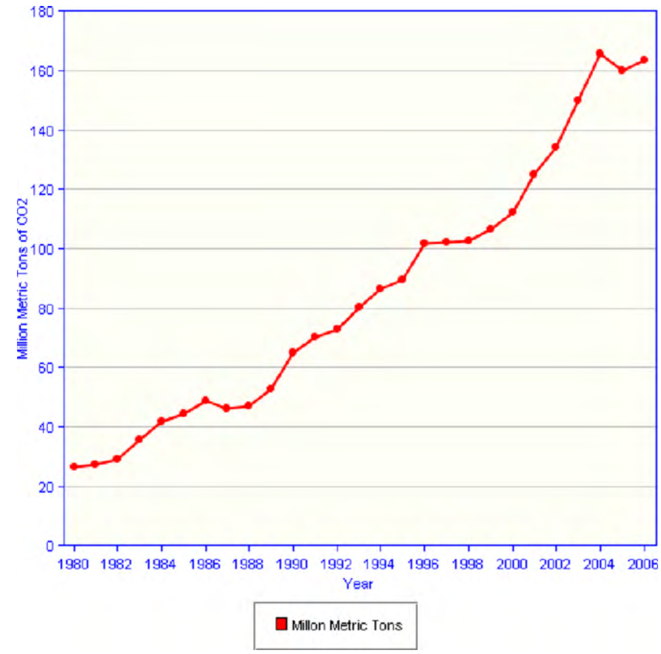
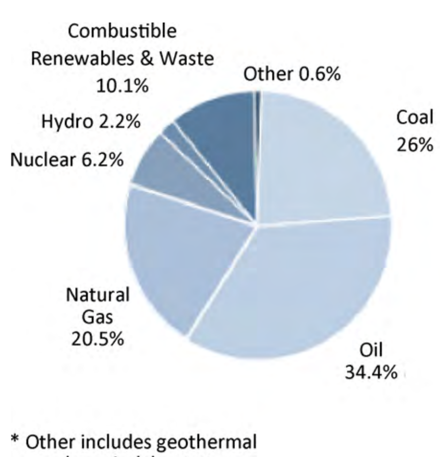


Fig. 7. Total CO_2 emission in Malaysia [19].

5. Coal-fired power plant

Fossil fuels will continue to dominate the energy scene and by 2030, it is estimated that they will still provide 80% of the global energy needs [25]. In fact, coal itself at present contributes 26% of the total world primary energy supply; behind only to oil at 35%. Also, 41% of the world's electricity is generated from coal, follows



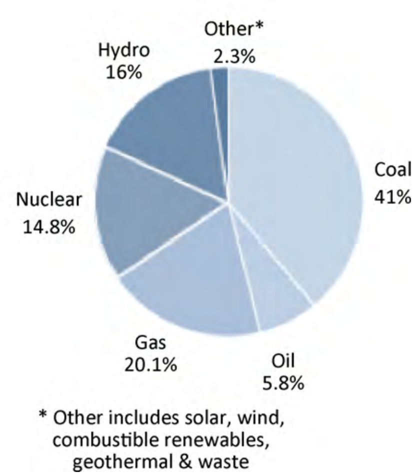


Fig. 8. Total world primary energy supply by fuel (left), and total world electricity generation by fuel [26].

Table 3
Top-10 hard coal producers in the world as in 2008 [34].

Country	Million tonnes (Mt)
China	2761
USA	1007
India	490
Australia	325
Russia	247
Indonesia	246
South Africa	236
Kazakhstan	104
Poland	84
Colombia	79
World	5845

Table 4
Top countries heavily dependent on coal for electricity generation as in 2007 [34].

Country	Percentage
South Africa	94
Poland	93
China	81
Australia	76
Israel	71
Kazakhstan	70
India	68
Czech Rep.	62
Morocco	57
Greece	55
USA	49
Germany	49

by natural gas (20%), hydro (16%), nuclear (15%), oil (6%) and others (2%) (see Fig. 8) [26].

Coal has long been and will continue to remain as one of the society's most secure forms of energy, offering many advantages: (i) abundant and globally distributed; (ii) major developed and developing economies have large indigenous coal reserves; (iii) readily available from a wide variety of sources in a well-supplied worldwide market; (iv) affordable and stable in price; (v) safe to transport and store; (vi) can be stockpiled at mines, power stations, or intermediate locations; (vii) coal-based electricity is well-established and highly reliable; (viii) not dependent on weather or rainfall; and (ix) coal is addressing its environmental challenges. The growing trend of its importance is evident as coal is also predicted to be the leading fuel for power generation globally in the foreseeable future for its estimated capacity to last for another 130 years, which is double that of natural gas and triple that of oil [27–33]. It is undeniable that more and more countries are becoming dependent on coal for energy consumption and electricity generation, with the power sector's share of global coal demand is forecasted to rise from 69% in 2002 to 78% by 2030 [31]. Tables 3 and 4 show the world's top coal producers and countries with the highest dependency on coal for their electricity generation, respectively [34].

Globally, CO_2 emission from coal consumption was nearly 13 billion metric tonnes in 2008. Of that total, USA alone with its consumption of more than 1.12 billion short tonnes of coal has accounted for 2.1 billion metric tonnes of emission from its over 8000 power plants out of the more than 50,000 worldwide, while China consumed 2.83 billion short tonnes and emitted 5.38 billion tonnes of CO_2 [35]. Together, USA and China have collectively accounted for more than half of the world's power-related coal consumption and CO_2 emission. Malaysia as a small developing country consumed 10 million short tonnes and emits 36 million metric tonnes as in 2008.

Table 5
List of coal-fired power plant in Malaysia [9,37,38].

Power plant	Capacity (MW)	Operation year	Annual consumption (mil. tonnes)
TNB Kapar (phase 2)	600	1988	1.50
IPP Sijingkat	220	2000	0.65
TNB Kapar (phase 3)	1000	2001	2.50
TNB Janamanjung	2100	2003	6.00
IPP Pulau Bunting	700	2005	1.75
IPP Tanjung Bin	2100	2007	5.25
IPP Jimah	1400	2008	3.50
New plants	1300	2011	3.55
Total	9520		24.7

Governments, industry, environmental non-government organizations (NGOs) and scientific representatives from over 15 key countries have agreed to accelerate the early global deployment of CCS in the G8 Summit workshop held in 2007 in Calgary, Canada, and concluded with an urgent call for the development of at least 20 industrial scale CCS projects worldwide by 2020. The G8 heads of government were urged to recognize the critical role of CCS in tackling global climate change and demonstrate the political leadership necessary to act immediately to initiate widespread deployment of this technology. There was also broad consensus by participants that market mechanisms, like emissions trading, will not be sufficient to mobilize early CCS projects and government assistance will be required to address the current financial gap to accelerate commercial deployment of CCS. The recommendations also highlighted the inclusion of CCS under the CDM by December 2008 as an important priority. The International Energy Agency (IEA) has estimated that, in addition to other mitigation options needed to combat climate change, CCS must be installed on the equivalent of 630 coal-fired power plants by 2030 [36].

As coal becomes more imperative, the number of coal-fired plants in Malaysia will undeniably continue to increase as demand for its usage in electricity generation grows and Malaysia can definitely benefit from the installation of CCS in its existing coal-fired power plants as listed in Table 5. Already, new plants have been proposed recently at several sites in Silam, Sinakut and Seguntur; all located in Sabah, a state in East Malaysia [39] and also the proposal to double the capacity of the current 2100 MW Janamanjung facility.

6. Cost of CCS

Implementing CCS technology to a coal-fired power plant to tackle climate change can be a huge investment; running into the range of hundreds millions of dollars for the possible costs incur from the capture and compression, transportation, and up to secured storage, depending on the type of plants. But it is almost impossible to halve CO_2 emissions by year 2050 without including CCS in the plan. Currently, the high cost of CCS appears to be the largest barrier to implementation. Estimated costs for CCS range from US$30–70 per tonne CO_2 depending mainly on the capture technology and concentration of CO_2 in the stream which it is captured [40]. CO_2 capture (separation and compression) alone will increase the cost of electricity from US$43 per MWh to US$61–78 per MWh for new power plants and from US$17 per MWh to US$58–67 per MWh for existing coal plants that have already been paid off. Separation and compression typically account for over 75% of the costs of CCS, with the remaining costs attributed to transportation and underground storage. Pipeline transportation costs are highly site-specific as they depend heavily on economy of scale and pipeline length. Costs of underground storage are estimated from US$3–10 per tonne CO_2 [41].

Table 6
Additional cost of CO_2 emissions reduction [29].

Cost of CCS	3 US$c/kwh (2.5 €c/kwh)
Current buy-out price for UK renewable	Over 5 €c/kwh
Premium for wind power under the German Renewable Energy Law	9 €c/kwh

In addition to the high cost of CCS, the energy penalty for capture and compression is also high. The post-combustion, end-of-pipe capture technologies use up to 30% of the total energy produced, thus dramatically decreasing the overall efficiency of the power plant. Oxy-combustion has a similarly high energy penalty because it requires separation of a pure source of oxygen from air, although eventually, new materials may offset the penalty by allowing for higher temperature and subsequently result in more efficient combustion. Pre-combustion technologies have the potential to lower energy penalties to the range of 10–20%, leading to higher overall efficiency and lower capture costs [10]. Nevertheless, if without CCS, it will be significantly harder and more expensive to stabilize atmospheric concentrations of GHGs, with the potential to cost an additional US$1.28 trillion for climate mitigation activities annually by 2050 [42]. From a different angle, adding CCS to a coal-fired power plant is relatively cheap in comparison to some renewable energy, as indicated in Table 6.

Several industrialized countries committed to emission reductions under the Kyoto Protocol are establishing a price on carbon emissions, with the most extensive scheme being the European Union Emissions Trading Scheme (EU ETS). The ETS imposes annual targets for CO_2 emissions on each EU country, and then in turn each country allocates its national allowance across those companies whose factories and plants are the major emitters of carbon dioxide – power utilities, building products manufacturers and other heavy industrial enterprises. As of January 2010, carbon is being traded at between €11–12 per tonne in the ETS. Besides the ETS, the CDM has established a carbon price on non-Annex I in order to allow the market to determine where it is cheapest to reduce emissions, which should significantly lower the cost of compliance globally. CER prices also track the European Union Allowances (EUAs), the emissions permits issued under the EU ETS [43].

Fig. 9 indicates the global average annual investment required in various renewable and alternative energy sources and technologies in order to combat the climate change effectively, which refer to a 50% reduction in CO_2 emission by 2050. Evidently, there is a lot of catching up to do for all the sources involved to achieve the objective. Coal-fired power plant with CCS needs to grow at an estimated rate of 18 GW/year from the present 500 MW per year, in order to achieve the 50% reduction target. A study conducted by the IEA on low-carbon technologies on their CO_2 mitigation further justified the significance of CCS, as illustrated in Fig. 10. The study predicted that the application of CCS on industry and power generation is capable to mitigate up to 19% of CO_2 by 2050, comparable to renewable energy at 21%. Since the EU and USA are most established in their CCS programmes, some of their planning are worth to take note of, such as [44]:

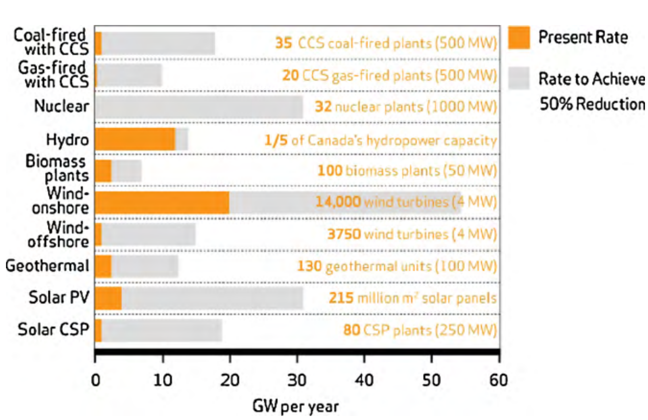


Fig. 9. Average annual power plant investment needed between 2010 and 2050 to reduce emission by 50% from current level [45].

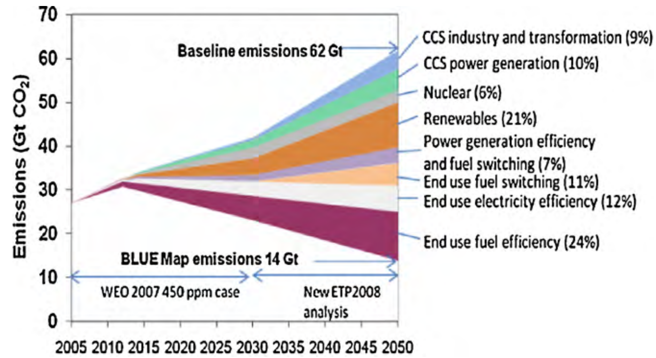


Fig. 10. Comparative contribution to CO_2 mitigation [45].

- From the EU's Impact Assessment of the Geological Storage of CO_2 conducted in 2008 found out that by building ten 400 MW coal-fired CCS power plants at a cost of €9 billion, will save €60 billion in abatement costs by 2030.
- It takes €5–13 billion in lifetime cost to build and operate the first 12 commercial scale coal CCS while the annual costs for EU to meet its renewable energy targets are €13–18 billion per annum.
- The abatement costs in UK through coal CCS is €60–90 for every tonne of CO_2 captured for the first CCS coal plants to year 2015 (from 2020 onwards, costs should decrease to €35–50) while through renewable energy, it costs €95–205.
- Deutsche Bank AG in 2007 estimated 100% auctioning of EUAs beyond year 2013 for power sector alone could raise €24 billion annually.

The USA's Pew Centre on Global Climate Change in 2007 estimated that by building thirty 400 MW coal-fired CCS power plants at a cost of US$30.1 billion, will save US$80–100 billion in abatement costs by 2030. Pew Centre further suggested that this could be financed through a levy on coal-fired power plants for 10 years at a rate between US$0.0012–0.0015 kWh.

7. CCS in coal-electricity generation

7.1. Choices of coal-fired power plants

CCS in Malaysia is still in its infancy, with the first commercial plant operational in 1999 at 200 tCO_2 per day recovery from a flue gas stream for urea production (equivalent to the emissions from a 10 MW coal-fired power plant) [45]. There are two main types of coal-fired power plants – pulverized coal (PC) and integrated gasification combined cycle (IGCC) power plants (see Fig. 11). IGCC power plant which applies pre-combustion capture is more efficient than PC-fired plant and would be a more attractive option as new plants [46]. Net efficiency for the existing IGCC plants is around 40–43% for the low heating value type and 38–41% for high heating value. Recent gas turbines would enable this to be further improved, and future developments should take efficiencies beyond 50% [47]. Unlike the ordinary coal-fired power plants,

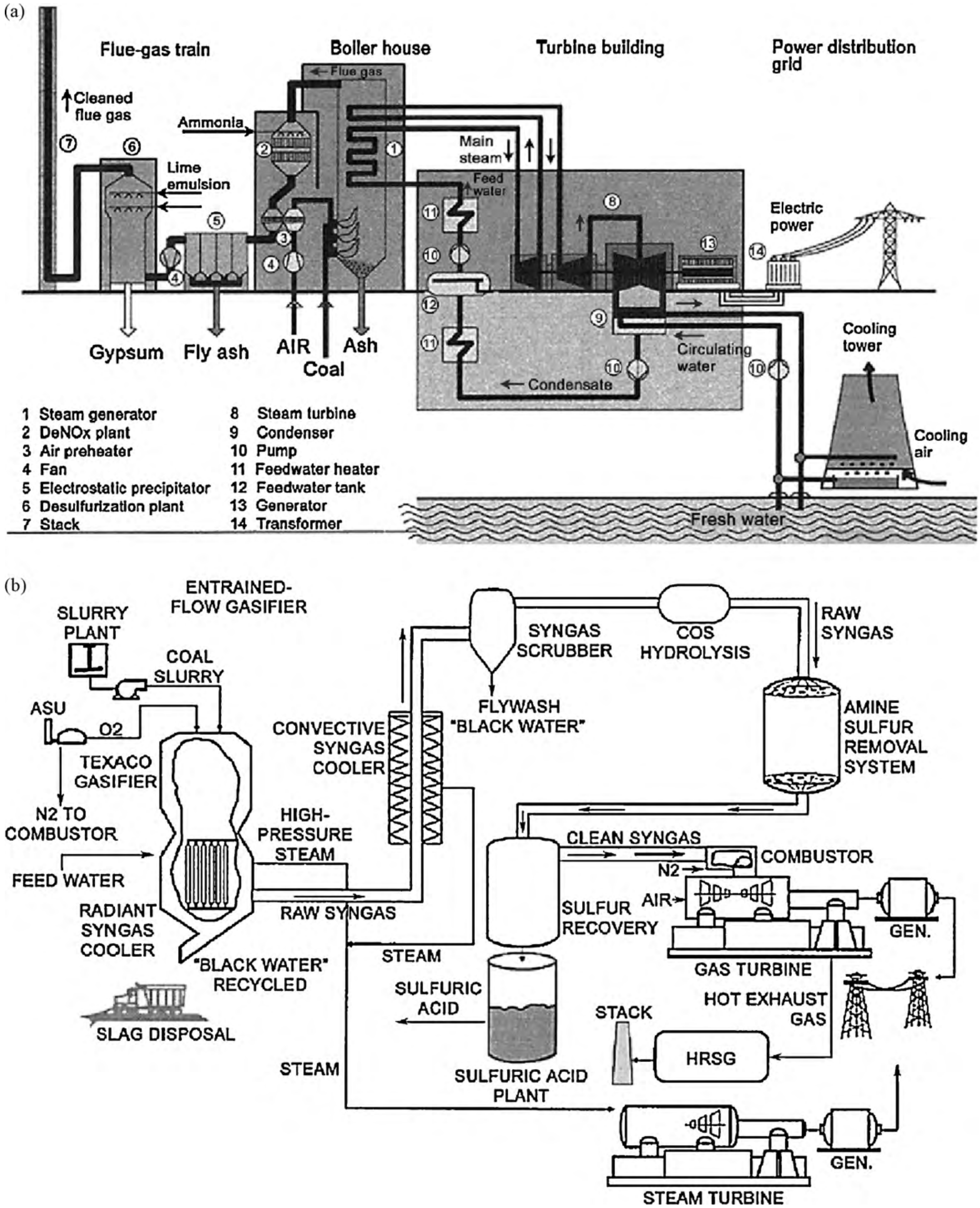


Fig. 11. Two main types of coal-fired power plants: (a) PC power generation system and (b) IGCC power generation system [49].

IGCC does not need to deal with low-concentration pollutants in large volume of flue gas. The gas emitted from the gasifier (syngas) of an IGCC system is under high pressure and contains higher concentrations of pollutants compare to the exhaust gas from coal combustion, thus resulting in comparatively lower cost to remove the pollutants. IGCC is a power generation process combining two leading technologies [48];

- Coal gasification – transforms coal to a synthetic gas (syngas). The gasification portion of the IGCC plant produces clean syngas which consists mainly of carbon monoxide and hydrogen, when coal is combined with oxygen. The syngas is then cleansed through the gas cleanup process before it is used in the combustion turbine to generate electricity.
- Combined cycle – one of the more efficient means in generating electricity. This portion consists of a combustion turbine or generator, a heat recovery steam generator and a steam turbine or generator. The exhaust heat from the syngas-fired combustion turbine is recovered in the heat recovery steam generator (exhaust-heat boiler) to produce steam which passes through a steam turbine to power up another generator which generates more electricity. The combined cycle is more efficient than any conventional power generating system in the sense that it reuses waste heat to produce more electricity.

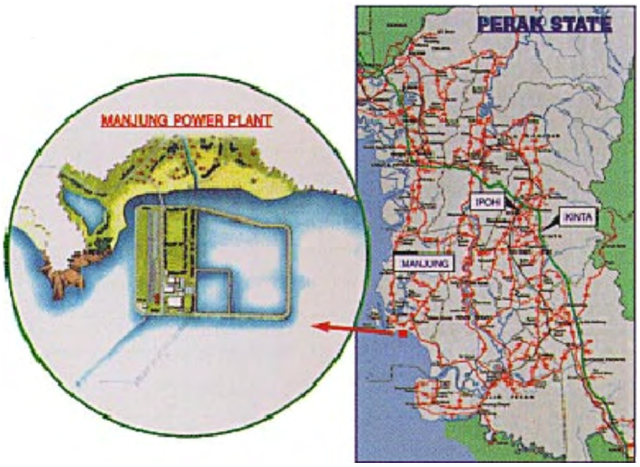


Fig. 12. Janamanjung power plant [50].

A recent project that worth mention here is when a team from Universiti Tenaga (UNITEN) has in last year proposed and presented a comprehensive case study on a CCS implementation of the end-of-pipe capture technology in the Janamanjung power plant at the Cooling the Planet competition in London and was honoured with a third finishing. The case study is deemed as a technically and economically viable mitigation measure and has the potential to kick-start a large-scale CCS application in Malaysia. The said power plant has an installed-capacity of 3×700 MW (2100 MW) in total and is located on a man-made island off the coast of Perak, west of Peninsular Malaysia (as shown in Fig. 12), making coal imports easier and convenient. According to the Malaysia Energy Centre, the average emission from this plant which uses bituminous coal (85% carbon content), 29 MJ/kg at 35% thermal efficiency is approximately 10 Mt CO_2 per year [51].

With the current available technology capable to capture 85–95% (8.5–9.5 Mt CO_2 per year) of CO_2 processed in a plant, only a small amount if CO_2 is emitted to the atmosphere. The team proposed to retrofit a post-combustion capture system which typically employs



Fig. 13. The peninsular gas utilization project in Peninsular Malaysia [52].

separation with amine-based absorption system. Across the full set of studies, CO_2 capture adds 44–87% to the capital cost of the reference plant (Janamanjung costs US$1.8 billion; hence US$0.792–1.566 billion) and 42–81% to the cost of electricity, while achieving CO_2 reductions of roughly 80–90% per net kWh produced [45]. This is followed by the transportation of the compressed CO_2 gas through a proposed novel alternate parallel pipeline running along the existing 1700 km PETRONAS peninsular gas utilization (PGU) project which is used to transfer natural gas from fields in offshore Terengganu [52], as illustrated in Fig. 13. This shall reduce the cost for transportation considerably. The PGU is a mature technology as similar great pipeline was built in1982 to supply CO_2 from McElmo Dome in S.E. Colorado that carries up to 20 Mt CO_2 per year to the CO_2 hub in Denver City, Texas [45]. The team has estimated an investment cost of between US$0.2–0.8 million per km for the parallel pipeline, depending on the length, diameter, amount and quality of the CO_2 to be transported [51]. Generally, it is very much possible to retrofit any coal-fired power plants (located along the west coast of Peninsular Malaysia) as long as it is situated near the PGU to take full advantage of its existing transportation convenience.

But then again, retrofitting existing coal-fired plants may not be economical and CCS may need to await replacement of existing generation capacity with new plants that are more efficient in capturing CO_2 [10]. With technology innovations and advancement in the CCS and coal plant design going rapidly, it might be more practical to build new plants integrated with CCS.

7.2. Types of capture technologies

There are basically four main capture technologies; absorption, adsorption, membrane and cryogenic separation. Out of these four technologies, only absorption and adsorption methods are suitable for larger power plants. This is because cryogenic separation (low-temperature distillation) requires much energy, thus result in higher operation cost. While separation by membranes is attractive (a principle similar to filtration), but most membranes are still in development phase, such as the one in [53], and not feasible for industrial scale yet [54].

Absorption has long been considered as a proven technology to capture GHGs, and its prevalent application widely used in many different sectors and industries for years. The mechanism behind this method in separating CO_2 is by employing solvents. These solvents work by either reacting with the CO_2 to produce a chemical which is subsequently dissociated by heating to recover the solvents and CO_2 (i.e., chemical absorption), or by physically absorbing the CO_2 under the pressure to recover the solvent and CO_2 by dropping the pressure subsequently (i.e., physical absorption). A typical absorption process utilizing MEA is shown in Fig. 3a.

Alternatively, adsorption (physical adsorption) process is based on the similar principle but is using porous solid adsorbents such as zeolites and activated carbon, and also chemical reactions between the adsorbents and CO_2 may or may not occur during the separation process [46]. Fig. 3b shows a typical adsorption process where it fundamentally consists of two major steps; adsorption and desorption. The technical feasibility of a process is dictated by the adsorption step, whereas the desorption step controls its economic viability. Strong affinity of an adsorbent for removing the undesired component from a gas mixture is essential for an effective adsorption step. The stronger the affinity, however, the more difficult it is to desorb the gas impurity and higher the energy consumed in regenerating the adsorbent for reuse in the next cycle. The desorption step, therefore, has to be carefully balanced against the adsorption step for an adsorption step to be successful [55].

Table 7
Operating condition [58].

Capture technology	Gas flow[a]	CO_2 partial pressure[b]	CO_2 concentration[c]
MEA absorption	High	Low	Low
Adsorption	Low	High	High

[a] A high gas flow is considered >150 m^3/s.
[b] A high CO_2 partial pressure is considered >7 bar.
[c] A high CO_2 concentration is considered >15% volume dry.

Table 8
Cost of reduction capture technologies [59,60].

Capture technology	Capital cost (million won[a]/MW)	Fixed O&M ('000 won[a]/MW)
MEA absorption	736	29,425
Adsorption	702	28,087

[a] US$1 = 1160 won.

Table 9
Efficiency and CO_2 emission reduction [56].

Power plant	Efficiency penalty (% points)	Emission rate of CO_2 (gCO_2/kWh)	CO_2 emission reduction (%)
IGCC with MEA chemical absorption	11	199	75
IGCC with PSA adsorption	15	61	92

Adsorbents can separate CO_2 from a stream by preferentially attracting it to the material surface at high pressure through weak interactions such as van der Waals force. The gas molecules are adsorbed onto the surface of the adsorbent and thus extracted from the stream. The adsorbent may then be generated either by applying heat or reducing pressure. There are several applicable adsorbents for CO_2 capture which include alumina, zeolite and activated carbon [21]. Regeneration of the adsorbent usually takes place either by pressure reduction (pressure swing adsorption, PSA) or by application of heat (temperature swing adsorption, TSA). However, PSA is claimed to be technically and economically more viable than TSA mainly because the former has shorter generation time (regeneration can be performed within seconds) than the latter which might take hours to accomplished similar generation [56]. For that reason, the main advantage of physical adsorption over chemical or physical absorption is quite evident from its simple and energy efficient operation and regeneration, which can be achieved with a pressure swing [55]. Despite this, other disadvantages of absorption process include consumption of significant amount of energy and it requires corrosive, degradable and volatile extractive chemicals. It also requires a new back-pressure steam generator, CO_2 scrubber/stripper and CO_2 compressor/dryer. In order to operate the CO_2 scrubber and compressor, additional energy of up to approximately 30% of the power plant output is required [57].

Additionally, the choice of capture technologies is predominantly influenced by the concentration or partial pressure of the gas to be captured [58]. It is crucial that they are applied in compatible operating condition in order to be optimal in both cost and efficiency, hence, the appropriate operating condition for both types of capture technologies are summarized and tabulated in Tables 7–9.

8. Sustainability and challenges

A main determinant of the future of coal is the crucial role in climate policy of the application of CCS to coal-electricity generation. Without emissions controls, coal is the cheapest fossil source for base-load electricity generation as it is widely distributed among developed and developing countries, raising fewer security concerns than oil and natural gas do. These advantages, combined with regional interests tied to coal, make it highly unlikely that coal can be substantially removed from power generation, thus making the success in developing and implementing CCS technology is a priority objective in the management of climate risk.

Any technologies that can prolong the use of fossil fuels, such as CCS, may be viewed with much scepticism. Furthermore, the energy penalty for capture, particularly of post-combustion capture, may be viewed as wasteful and undesirable. Risk of local and regional environment impacts and the ability to anticipate and avoid them will be crucial. On-the-ground pilot and demonstration projects will draw both interest and concern from neighbouring communities. Public acceptance remains one of the biggest hurdles to overcome in the realization of large-scale CCS implementations. Concerns such as human safety, environmental impacts, property values, job opportunities, financial compensation and economic growth will probably be hotly debated, and how these concerns individually and collectively transpire will be critically important in determining whether CCS will gain public acceptance or not [10]. There is much coverage on CCS in the media, forums and conferences over the past several years. As more people are exposed to the idea of CCS, public opinion and awareness will be shaped. But judging from the current condition, it is only fair to say that public awareness is still low on the concept of CCS.

The high costs in CCS implementation, especially in CO_2 storage, which at in the order of US$0.5–5 per tCO_2 for onshore and US$6–12 per tCO_2 for offshore [45] respectively, will always be a drawback. While this metric may be useful in comparing the cost of CCS with other CO_2 emissions reduction method, the increase in costs of electricity generation may be a more meaningful economic metric because the power sector will provide the biggest benefit from CCS [10]. But any hike in electricity costs resulting from CCS may and most likely be translated to higher consumer's tariff and this, without doubt, is never a popular move and unless the government subsidizes part of the costs, this will have a significant impact on its acceptability.

The lack of appropriate legal regulatory frameworks for CCS and institutional issues such as regulatory oversight are also one of the main obstacles facing the countries which have implemented CCS and this must be addressed properly if Malaysia were to follow suit in its CCS quest. The regulatory frameworks shall include items such as the definition or classification of CO_2, access and property rights, intellectual property rights, monitoring and verification requirements, and liability issues, which are all discussed in length in [61]. A consistent effort to address the major unresolved regulatory issues related to CCS, such as long-term stewardship of the stored CO_2 is required for rapid implementation of the technology, and it is good to know that concerted efforts are underway in the development of national- and international-level rules and regulations for CCS projects such as in [62] and [63] for instance.

9. Conclusions

CCS as a technology builds upon a technology-base developed more than half a century by the oil and gas industry, is now being implemented in some situations today as a necessary tool to alleviate CO_2. It is just a matter of time before CCS is going to be implemented in coal-fired power plants in Malaysia. CCS is no longer seen as an option, but a necessity in order to heal the ailing mother's earth. Immediate and significant benefits from this

approach are obviously the luxury to continue to use the plenteous and inexpensive coal for power generation while at the same time, build a smooth and steady economic transition towards a low-carbon future. But significant technological improvements which shall lead to cost reductions are also on the horizon, which hopefully can lead to a much wider application than now.

The task to implement CCS to the coal-fired power plants in Malaysia remains very much challenging, yet absolutely achievable. The challenge is best put into context by considering the scale of the undertaking. For the size of the Janamanjung power plant, current existing CCS technology is enough to support an attempt of this scale. Besides establishing extensive regulatory frameworks and policies for CCS, overview of the geological or oceanic storage is also crucial, such as storage site selection, performance prediction and risk assessment. As the costs will remain as a major concern with the limited government funding in green technology, the widespread use of CCS will only materialize with large investments from the private sectors and institutional commitments.

But if we were to look beyond year 2050, when CCS is to capture billions or even trillions tonnes of CO_2 emissions from fossil fuels combustions, besides the need for thousands of such projects, numerous advances are needed as well. Technological innovations to reduce the cost of capture, for instance, better separation technologies, technological advances in turbine design to support repowering with advanced generation systems and systems optimization, will be imperative to achieve the goal. If CCS is successfully adopted in Malaysia and hopefully every other country, coal utilization will definitely expand with the stabilization of CO_2 emissions.

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